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THE USE OF ERTS-I SATELLITE DATA
IN GREAT LAKES MESOMETEOROLOGICAL STUDIES

GSFC ID UN 144   CONTRACT NAS5-21736

submitted by

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PROGRESS REPORT

THE USE OF ERTS-1 SATELLITE DATA
IN GREAT LAKES MESOMETEOROLOGICAL STUDIES

by

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b. PI: WALTER A. LYONS
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c. PROBLEMS ENCOUNTERED:

The following is a summary of some of the difficulties which
have been encountered. They are not necessarily ranked in order
of importance.

1. We have had relatively poor luck with weather conditions at
the time of ERTS passage in this area, at least with respect to
our air pollution studies. Several times they have been IFR condi-
tions, making flying with the CESSNA aircraft impossible.

2. We are still greatly hampered by lack of funds. This is a
no-cost contract. Our hopes for the quality of the ERTS data
were greatly exceeded, and to be able to utilize even a fraction
of the valuable data being received, we have to find "soft money"
in other accounts. This is being done, but at a slow rate.

3. Much our planned analysis in the original proposal was
dependant upon obtaining large amounts of surface, radar and sate-
llite data over the Lake Ontario basin through the NOAA/IFYGL
project. However, to date we have received virtually none of the
promised data, and thus a vital portion of our "ground truth" for
the Lake Ontario region is not on hand.

4. During the winter months, numerous small snags developed with
the instrumented aircraft system which prevented a full-scale test
and shake down of the new sensing package until just recently.

5. We continue to find a considerable time delay in receiving
some data, as much as three months in some cases.

6. The nine station Air Quality Monitoring Network for Milwaukee
county is only partially operational at this time, due to start-up
difficuties. This removes some data from the Milwaukee area ground
truth.

7. Our all-sky time lapse camera system in Milwaukee was vandal-
ized, which has temporarely limited a portion of the photography
program.   2

d. ACCOMPLISHMENTS:

A number of important strides have been made in expanding our ability to use ERTS data in a number of various mesometeorological projects. They are listed below, not nexessarily in order of importance.

1. We have now finally completed cataloging the large number of transparancies and prints that have been received, due mainly to an increase in clerical help available from other sources to assist in the ERTS project.

2. Plans have finally been approved for the construction of a roof top observatory, for cameras and balloon tracking. Atop the 200 foot Engineering and Math Sciences Building at UWM, this platform, when available by fall, will allow for completely unobstructed all-sky cloud and smoke photography. Heretofore we have not been able to locate a site with a completely unobstructed horizon.

3. Plans are finalizing for an air pollution field study in the Milwaukee area in June and July, 1973. Weather permitting, every attempt will be made to achieve maximum data taking capabilities on days with ERTS overflights. At least 36 persons will be involved.

4. Arrangements are now being made to attain Air Force DAPP 1/3 mile resolution photographs of our operational area, for comparison with ERTS images.

5. We continue to take all-sky cloud pictures around the Lake Ontario basin. These will eventually be compared with ERTS views of the region.

6. ERTS images have already been used in classroom situations by graduate students at UWM. Several papers are being produced on such topics as "Sub-Mesoscale Gravity Waves" and "Great Lakes Snow Squalls".

7. The GLUMP Regional Air Pollution Diffusion Model is being perfected. Its predictions of Mesoscale particualte pollution patterns will eventually be used to compare haze patterns detected by ERTS, especially in MSS Band 4.

8. Of the results already reported to NASA from our various projects, most have been shown on prime time Milwaukee television (WTMJ-TV) and have met with great public response. Also, the principal investigator has given approximately ten public lectures to date on "RESULTS FROM ERTS", similarly with extremely enthusiastic audience response.

GREAT LAKES MESOSCALE SNOW SQUALLS
(subdiscipline - 6A: Mesoscale Processes)

1.   On October 19, 1973, a record early season snow struck the southern
shoreline of lake Michigan, with as much as 4-5 inches of snow in the
Chicago Loop. ERTS-1 images (ID No. 108816043) clearly revealed a well-
defined spiral vortex, about 50 km in diameter, over the lake east of
Chicago. The vortex was imbedded within a northeast wind. It has
long been postulated both from numerical models (LaVoie's) and from
surface pressure observations at the east end of Lake Ontario that such
disturbances accompanied the most intense lake snow squalls. While
vortices do occaisionally appear over oceanic regions in high resol-
ution satellite views of oceanic regions experiencing extreme cold air
advection, this is the first such event noted on the Great Lakes.
Studies are now continuing, including calculations of surface heat
fluxes and vorticity generation due to the quasi-circular heat source
that southern Lake Michigan represents.

2.   The LaVoie numerical model of Great Lakes snow squalls predicts
that as convection becomes more intense, the numerous small bands of
clouds which form over the Lakes will gradually congeal into one
major snow squall band running parallel to the low-level winds. Radar
studies have confirmed this. Several excellent ERTS images however
now have yielded the best mesosynoptic visual image of the phenomenon.
One of the better examples occurred on Lake Ontario, 20 January 1973,
ERTS ID No. 117215294. Other ERTS views of Lake Snows will be
compared to Air Force DAPP one-third mile resolution pictures, taken
almost simultaneously. It is planned that in the near future, it will
be feasible to use ERTS images in partial verification of certain
aspects of numerical models.

3.   One of the most startling findings with ERTS images are the
occasional extreme sensitivity of cloud patterns to topographic
variations, mainly abrupt changes in roughness lengths. The best
case to date is ERTS ID No. 114115585, taken over western lower
Michigan, 11 December, 1972. Here, weakly organized cumulus clouds
were present over Lake Michigan, with a hint of a polugonal Rayleigh
cellular pattern evident over the water. But as the clouds passed
over the 100 m high bluffs and dunes on Michigan's western shore,
there immediately appeared longitudinal cloud bands, and the cloud

cover increased from scattered to nearly overcast. Also, in a band about 20 to 40 miles inland, what appears to be glaciation takes place in the clouds. Underneath these glaciated cumulus, light snow flurries were reported. Continued inspection of ERTS views is finding similar phenomena along shorelines.

GREAT LAKES CONDUCTION FOGS
(Subdiscipline - 6B: Air/Surface Interactions)

During spring and early summer, the waters of the Great Lakes are frequently much below the temperature and dewpoint of advecting airmasses. The resulting conductive cooling produces intense but shallow inversions, often only 50 to 150 m in depth. The intensities of these inversions have been measured approaching $30^{\circ}C/100$ m. Fog frequently forms over the lakes under such circumstances. However, the fog is shallow, and when it advects onto shoreline areas on warm sunny days frequently dissipates in a matter of several hundred meters. Regular satellite images do show this phenomena, but some extremely interesting details have not been seen. Spectacualr views of conduction inversion fogs were obtained on 30 March, 1973 (ERTS ID No.1250160045) and 18 April, 1973 (ERTS ID No. 1269161101   ) over Lake Michigan. In particular, numerous wave patterns in the fog were seen. These included upwind standing waves near the Indiana Dunes and numerous patterns that look suspiciously like refraction patterns where the stable lake air impinges on the bluffs ringing the shoreline. Analysis of the picture is now in progress. A numerical model for predicting fog formation over the lake is now being developed and tested. A paper is in preparation.

3. QUANTATIVE EVALUATION OF COSTS AND BENEFITS:
   a. In the simplest case, we need not do anything more complicated
      than making a print from the negatives supplied. The vast
      majority of our analysis is visual interpretation. Automatic
      pattern recognition techniques are clearly applicable to our
      studies, but this work must await a second round of funding.
   b. Simple ERTS images, by themselves, have provided us with
      numerous opportunities for original atmospheric research. At
      the current rate, we estimate ten publishable articles of
      significant interest can be generated from our group alone.
4. QUANTATIVE ASSESSMENTS OF COSTS/ BENEFITS:
   Not applicable, except that much of our current research thrust
   simply could not exist without ERTS imagery.

GRAVITY WAVES FROM MOUNTAINS
(subdiscipline - 6A: Mesoscale Processes)

It has long been known that when stable air flows over topographic barriers, such as mountain ridges, that complex gravity wave patterns result. The early TIROS satellite often showed such "standing wave clouds" in such regions as the Appalachian Mountains. A number of excellent views of this phenomenon have been obtained by ERTS however (ID No. 1297 15234   ) . Not only are the lenticular wave clouds unambiguously identifiable, but the excellent ground imaging makes it extremely easy to relate the cloud forms to topographic features.

CUMULUS CLOUD DISSIPATION BY LARGE LAKES
(Subdiscipline - 6A: Mesoscale Processes)

It is a well established fact that typical daytime cumulus convective clouds have their origins within the surface superadiabatic year which exists over land on days with considerable insolation. Over cold lakes however, no such thermally unstable layer is found. Clouds drifting over cold lakes quickly dissipate and no new ones reform. Thus cloud-free lakes and cloud-free zones on downwind shorelines are often seen. Conventional satellite views however, while they show the general pattern, do not have adequate resolution to monitor individual clouds or cloud streets. Many views over the Great Lakes of cloud dissipation in spring and summer have now been obtained, such as ERTS ID No. 1263 15361 . These are most valuable to several ongoing projects attempting to model air-lake interactions of this type. Also they will be used as additional data in a major study of the energy budget of Lake Ontario, specifically, the compilation of a mesoscale insolation climatology of that lake.

ESTIMATES OF COST / BENEFITS

Our work at this time is basically directed to research rather than direct applications, though the future may well see such a development.

1. PRACTICAL APPLICATIONS:
   a. Virtually all of our work has been based on catch-as-catch-can observations. Numerous mesoscale phenomena are always occurring in the atmosphere over the Great Lakes. Ideally we might prefer to have daily, or even more frequent observations. However, from a purely research point of view, much is obtainable from the current system. For certain studies (clouds) the resolution is more than enough. For others, smoke plumes, etc., even greater resolltion would be useful. The 1000 LST over flight time is acceptable, but for many of our convective cloud studies, an early afternoon time would be better.

   b. At the current time, no agencies are using our exact data. Potentially, however, such groups as the Wisconsin State Department of Natural Resources might wish to use ERTS-type data to monitor interregional pollution transport into southeast Wisconsin from Chicago-Gary. Also, snow squall cloud monitoring, especially if glaciation can be routinely and automatically detected, might be of inestimable value in upcoming years when operational cloud seeding of lake snows becomes a reality.

   c. Our group per se is not a decision making agency.

2. QUALITATIVE COSTS AND BENEFITS:
   a. In virtually all cases, ERTS provides a unique source of data for our meteorological studies. Thus it can not be compared to any other source.

   b. Again ERTS is unique. Its closer competitor for cloud studies is the Air Force DAPP data. However that satellite does not have multispectral capability, which may well prove to be extremely useful as studies continue.

   c. These data will be of imense value in directing our future research efforts. In that sense, they will greatly help in wisely utilizing federal research monies.

e. SIGNIFICANT RESULTS:

LAKE BREEZE POLLUTION PATTERNS
(Subdiscipline - 7A: AIR POLLUTION)

A remarkable view of particulate air pollution was discovered in the vicinity of Buffalo, New York, on 20 June 1973 (ERTS ID.   ). There was a classic all-shore lake breeze in progress, and it was obvious that dense smoke was present to the west of Buffalo over Lake Erie. This smoke was the pollution that had been produced by sources in the area which had been undercut by the inland rushing lake breeze front and which was then being advected lakewards in the return flow layer aloft. It is precisely this phenomena, the recirculation of pollutants in the lake breeze, that is the object of the full-scale EPA support field project being directed by the University of Wisconsin-Milwaukee in summer 1973.

f. PRODUCTS

In the past six months, we have begun to move a number of our ERTS results towards publication and dissemination:

(1) "ERTS-1 Views the Great Lakes", paper presented at NASA symposium, GSFC, Greenbelt, Md., March, 1973. Manuscript submitted for proceedings.

(2) "ERTS-1 Views the Great Lakes", with S.R. Pease, slide presentation (120 slides) to, 16th Conference on Great Lakes Research, International Association for Great Lakes Research, Sandusky, Ohio, April, 1973.

(3) "Detection of Particulate Air Pollution Plumes from Major Point Sources Using ERTS-1 Imagery", with S.R. Pease, submitted to Bulletin, American Meteorologycal Society, also UWM-APAL Report No. 10, in press. Copy of draft enclosed.

(4) "Inadvertant Cloud Seeding by Chicago-Northern Indiana Pollution Sources Observed by ERTS-1", submitted to Monthly Weather Review, also UWM-APAL Report No. 9, in press.

(5) Two abstracts have been submitted for the American Meteorological Society's Annual Meeting, Honolulu, December, 1973:

"ERTS-1 and Air Force DAPP Satellite Images of Dynamical Features of Great Lakes Snow Squall Mesosystems", with Glenn E. Stoutt, Illinois State Water Survey.

"Great Lakes Springtime Conduction Fogs: Numerical Study and ERTS-1 Observations".

(6) A slide presentation (over 200 in collection) of various results from ERTS has been presented to date in ten public lectures, and also given considerable exposure on WTMJ-TV (NBC, Milwaukee).

g. RECOMMENDATIONS:
None

h. CHANGES IN STANDING ORDER:
None.

i. ERTS IMAGE DESCRIPTOR FORM:
Attached.

j. DATA REQUEST FORMS:
None to date.

APPENDICES

ERTS IMAGE DESCRIPTOR FORM

USER NAME __Walter A. Lyons__   DATE __30 April 1973__

USER ID __UN 144__

AGENCY __Univ. Wisconsin-Milwaukee__

PRODUCT ID (INCL. BAND AND PRODUCT)	FREQUENTLY USED DESCRIPTORS *			DESCRIPTORS
	Snow Squalls	Mesoscale Grav. Wvs.	Contrails	
1 137 15355X	x			Cloud Streets
1 137 15362X	x			Cloud Streets
1 172 15294X	x			Cloud Streets
1 172 15292X	x			" "
1 250 16045X				Fog
1 250 16052X				Fog
1 105 15575X		x		
1 119 15350X		x		
1 108 16150X		x		
1 108 16144X		x	x	
1 118 15303X		x	x	
1 153 15242X			x	
1 135 15242X		x		Cumulus, Fog
1 263 15361X				
1 263 15364X				Cumulus, Fog
1 088 16043X	x			
1 172 15294X	x			
1 141 15585X	x			
1 269 16101X				Fog
1 297 15234		x		

FOR DESCRIPTORS WHICH WILL OCCUR FREQUENTLY, WRITE THE DESCRIPTOR TERMS IN
COLUMN HEADING SPACES NOW AND USE A CHECK (✓) MARK IN THE APPROPRIATE
COLUMN. FOR OTHER DESCRIPTORS, WRITE THE TERM UNDER THE DESCRIPTORS
COLUMN.

MAIL TO   ERTS User Services
             Code 563
             Bldg 23 Room E203
             NASA GSFC
             Greenbelt, Md. 20771

ERTS-1 AND AIR FORCE DAPP SATELLITE IMAGES OF DYNAMICAL FEATURES OF GREAT LAKES SNOW SQUALL MESOSYSTEMS

by

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A new generation of high resolltion satellite sensors have recently become available for mesoscale cloud studies. ERTS-1 is producing multispectral scanner images with resolutions approaching 50 meters. The recently declassified Air Force DAPP satellites are providing synoptic views in the visible with resolutions approaching one-third mile.

These data are being used to investigate mesoscale snow squall systems over the Great Lakes. On 19 October 1972, the Chicago area received a record early snow associated with an outbreak of Arctic air. The ERTS picture revealed a clear-cut spiral vortex embedded within a major snow band traversing Lake Michigan. Such vortices have been suspected from microbarograph networks on the eastern end of Lake Ontario and appear in LaVoie's numerical models of lake snow squalls, but this is the first known clear-cut observation. Simple heat flux estimates are made for the southern basin of Lake Michigan, and the vorticity generation for such a quasi-circular is calculated.

Other satellite views have shown some interesting responses of lake snows to orographic features. For example, near the eastern shore of Lake Michigan, which is lined with 100m high bluffs and dunes, weakly organized cellular cumulus clouds are transformed within a matter of a kilometer into a nearly overcast longitudinal banded pattern. About 20km further inland the clouds apparently glaciate producing snow at the surface. Similar phenomena are being noted on a regular basis.

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DETECTION OF PARTICULATE AIR POLLUTION PLUMES
FROM MAJOR POINT SOURCES USING ERTS-1 IMAGERY

by

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May, 1973

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DETECTION OF PARTICULATE AIR POLLUTION

PLUMES FROM MAJOR POINT SOURCES USING ERTS - 1 IMAGERY[1]

Walter A. Lyons and Steven R. Pease

ABSTRACT

The Earth Resources Technology Statellite (ERTS-1) launched
by NASA in July, 1972 has been providing thousands of high resolution
multi-spectral images of great interest to geographers, cartographers,
hydrologists, agriculturists, etc. The meteorological content of
these observations, however, has only been slightly realized. In
particular, it has been found possible to detect the long-range
(over 50 km) transport of suspended particulate plumes from the
Chicago-Gary steel mill complex over Lake Michigan. The observed
plumes are readily related to known steel mills, a cement plant,
refineries, and fossil-fuel power plants. This has important rami-
fications when discussing the inter-regional transport of atmospheric
pollutants, in this case from the Chicago Interstate to the Southeast
Wisconsin Air Quality Control Region. Analysis reveals that the
Multispectral Scanner Band 5 (0.6 - 0.7 micrometers) provides the best
overall contrast between the smoke and the underlying water surface.

1. Introduction

The Federal Clean Air Act of 1967 (amended 1970) divided the
United States into Air Quality Control Regions (AQCR). The boundaries
of these regions were ideally to be chosen to delineate independent
self-contained "air sheds" where air quality levels would be determined
by dispersion from sources within that region. The actual boundaries
selected often were compromises between meteorological and political
realities. An AQCR's final compliance with national Air Quality
Standards is ultimately dependent upon the successful formulation and
implementation by regional authorities of the necessary emission
control strategy for sources within that region. In reality, however,
two adjacent AQCR's might occasionally find themselves breathing
each other's effluents due to long-range inter-regional transport of
pollutants. A case in point is the Southeast Wisconsin AQCR (the
seven counties of southeastern Wisconsin, including metropolitan
Milwaukee) and the Chicago Interstate AQCR (northeast Illinois and the
two northwesternmost counties of Indiana). In the latter, there
exist numerous extremely large point sources, especially of suspended
particulates from steel mills, fossil-fuel power plants, refineries, and
cement operations. The evidence has gradually been accumulating that
these sources are indeed more than just local problems.

In August 1967, the principal author participated in a flight of
an NCAR Queen Air instrumented to monitor ice nuclei (Langer, Biter,
and Dascher, 1968). The object of the study was the dispersion of
anthropogenic ice nuclei emanating from the Chicago-Gary steel mill
complex. Under conditions of brisk southwesterly flow over southern
Lake Michigan, with a rather strong synoptic-scale capping subsidence
inversion around 1300 m, a clearly defined plume of ice nuclei was
easily tracked to the vicinity of Battle Creek, Michigan (some 90 km
downwind). More recently, on a spring day with south-southeast flow
up the lake, elevated layers of red iron-oxide smoke were seen drifting
past Milwaukee (Fig. 1). Again the most likely origin of this smoke
was the mills at the southern end of the lake - almost 70 km away.

The effect of the much larger Chicago Interstate AQCR is probably significant, but most difficult to ascertain qualitatively. It has been estimated that approximately 10% of the suspended particulates measured in the Milwaukee area originate in and around Chicago[2]. Frequently in Milwaukee, several hours after the surface winds shift to the south or southeast, there is a rapid increase in haze and smoke, presumably the influence of inter-regional transport from the Chicago area. Certainly in any megalopolis, such as found along the East and West Coasts, adjacent AQCR's would indeed be expected to be exchanging pollutants.

In the emerging Great Lakes megalopolis, which shows signs of extending from Green Bay, Wisconsin to Buffalo, New York in the not-too-distant future, the peculiar meteorological effects of the Great Lakes often exacerbate this inter-regional transport. When continental air masses advect across the relatively warm lakes in winter, any plume moving over a Great Lake will be rapidly dispersed. Turbulence generated by the free convection rising from the surface can be extreme, sometimes to the point of generating a myriad of miniature waterspouts or "steam devils" (Lyons and Pease, 1972). Thus if plumes from northern Indiana are to pass over Lake Michigan to southwestern Michigan or Wisconsin, they probably arrive diluted to an extreme degree. From early spring through late summer, quite the opposite situation prevails; air temperatures frequently exceed those of the lake by 10, 20 or sometimes 30° C.. Extremely intense, though shallow (100-200 m) surface conduction inversions form over the lake (Lyons, 1970). Air streams advecting over cold lakes not only are rapidly cooled in their lowest layers, but due to the absence of upward convective heat transport do not warm and destabilize in the overlying layers as occurs over land during the day. The almost total lack of cumulus clouds over the Great Lakes on summer afternoons is one manifestation of this (Lyons, 1966). A plume from a large elevated point source such as a steel mill or power plant may

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[2] A Statewide Implementation Plan to Achieve Air Quality Standards for Particulates, Sulfur Oxides, Nitrogen Oxides, Hydrocarbons, Oxidants, and Carbon Monoxide in the State of Wisconsin, regulations proposed by the State of Wisconsin, Department of Natural Resources, January, 1972.

travel for long distances over water with relatively little dilution
and arrive on a downwind shoreline in still very high concentrations.
Figure 2, a plume from a large fossil fuel power plant south of Milwaukee,
dramatically illustrates the point[3]. This plume could be seen extending
over 100 km to the east with minimal dispersion evident. If such a plume
arrives on a downwind shore during mid-day and insolation is sufficient,
it is fumigated to the surface after a few km of inland travel (Lyons
and Cole, 1973) and may cause high pollution levels, the origin of which
could be quite baffling to local control officials.

That there is inter-regional pollution transport in the vicinity
of the Great Lakes is clear, but measurement of actual amounts is a
problem. Until recently, reliable instrumentation for measuring total
suspended particulate matter using an aircraft in real time was not
available. Even with technology providing the measuring device, obtaining
a quasi-synoptic profile of plumes extending for at least 100 km down-
wind from an area as large as Chicago-Gary is both difficult and expensive,
particularly if such measurements are needed on a semi-regular basis.
The ideal solution would be a satellite monitoring system. Until recently
no satellite was capable of such observations, but with the launching of
NASA's Earth Resources Technology Satellite (ERTS-1) on 23 July 1972,
the prospect has improved markedly.

2. The Earth Resources Technology Satellite

ERTS was designed specifically for environmental monitoring. It
was placed in a nearly circular, 99.11 degree orbit, nominally about
915 km, with a 103.267 minute period. The sun-synchronous orbit has a
descending node time. Images are 185 by 185 km on a side. It takes 251
revolutions (18 days) to make one complete global coverage. Thus every
portion of the earth (between 81 degrees north and south latitude) is
viewed at least once every 18 days. At the latitude of Chicago, there
is approximately 35% horizontal image sidelap, so some locations can be
seen on successive days. A one-year mission life was contemplated, and
as of March 1973, more than 34,000 images had been collected. All images
are characterized by a zero or near-zero zenith angle, with illumination

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[3] Subsequent to the taking of this photograph in 1971, the particulate
emissions from this power plant were largly eliminated.

depending on the solar elavation angle, a function of date and latitude of observation.

The two great advantages of ERTS are its extremely high resolution and a multi-spectral imaging capability. The original specifications for the multi-spectral scanner (MSS) called for 100-200 m resolution. Initial results have shown some high contrast targets as small as 50 m. Highways, airport runways, small ponds, jet contrails, harbor break-waters, etc., are routinely visible. The four spectral bands are (1) MSS-4, 0.5-0.6 micrometers ("green" band), (2) MSS-5, 0.6-0.7 micrometers ("red" band), (3) MSS-6, 0.7-0.8 micrometers, and (4) MSS-7, 0.8-1.1 micrometers ("near infrared" band). ERTS products are available in several formats including digital tapes, 9 1/2 by 9 1/2 inch black and white and color prints and transparencies, and most routinely, 70mm negatives and positive transparencies. (Mac Callum, 1973).[4]

Because the four spectral bands are viewed simultaneously in space and time, it is possible to use color-additive viewing techniques to produce color-coded results. Combining bands 4,5 and 7 results in a false-color infrared image. The red color associated with foliated vegetation is a valuable diagnostic tool in agriculture, forestry, and land-use studies, but for the meteorologist it is most useful in pene-trating thick haze, revealing cloud shadows, delineating snow cover from vegetation, and demarcating land/water boundaries.

The various design characteristics prompted the UWM Air Pollution Analysis Laboratory to submit a proposal to study ERTS-1 data. Before launch, it was hoped that a satellite with these characteristics would be capable of detecting major plumes of suspended particulates, making possible synoptic studies of inter-regional pollution transport over the southern Lake Michigan basin.

3. The Study Area

The heart of the Chicago-Gary industrial complex stretches from the southeastern part of the City of Chicago eastwards along the shoreline of Lake and Porter Counties, Indiana, to east of Gary. Figure 3 is an aerial view of a part of this region, taken from an NCAR Queen Air at an altitude of about 2000 m. early on the morning of 15 July 1968, when brisk southwesterly flow was advecting numerous smoke plumes over the lake.

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[4] Details on ordering ERTS products can be directed to: The EROS Data Center, U.S. Dept. of the Interior, Geological Survey, 10th and Dakota Aves., Sioux Falls, S.D., (605) 339-2270.

A total of 16 major particulate sources have been located in the study area (Figs. 3 and 5). The estimated annual output of particulates (provided by local air pollution control officials) and the source type are listed in Table 1. The size of some of these sources is truly remarkable. Source 3, for example, a cement plant, discharges over 140,000 tons/year particulates. In comparison, all of Milwaukee County, Wisconsin, a relatively industrialized area, had a 1970 suspended particulate emission of only approximately 45,000 tons/year.

4. The Observation

During the morning of 1 October 1972, brisk southwest surface flow covered the southern Lake Michigan basin area (Fig. 4). A bank of alto-cumulus clouds, associated with a trough, was present to the north and east of the Chicago region and was moving rapidly northeastwards. A strong nocturnal radiation inversion had been present at 0600CST according to the Peoria, Illinois (PIA) sounding (inset, Fig. 4). The synoptic situation was thus similar to that when the aircraft photograph shown in Fig. 3 was taken. Figures 5 and 6 are portions of the ERTS images taken at approximately 1003CST.[5] They have been enlarged to show a region approximately 90 nm wide. Figure 5, in band MSS-4, appears to be a relatively low contrast image. Any plumes emanating from the steel mill complex are barely discernable, the radiance of the lake surface being so large as to be comparable to that of the smoke plumes in that portion of the spectrum. The 1000CST airway observations are superimposed. However, in Figure 6, band MSS-5, a number of particulate plumes can be seen streaming north-eastward, disappearing beneath the altocumulus cloud deck at a distance of about 60 km. The solar elevation angle is approximately 40°.

It should be noted that due to the various degradations involved both in making the photographic print and in publication, the plumes do not appear as clear as in the original 70-mm negatives. The prints were also photographically dodged to maximize details over both land and water.

The plumes in these images, for the most part, are combinations from several point sources. The most pronounced plume, from source eight (8), is not exclusively from a single stack, but from an entire mill complex, with one stack dominating. The total spread of the visible plume at 60 km

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[5]NASA ERTS Image Identification Number 1070 16041

downwind is about 4.5 km. The plume apparently emanating from source 2
actually is the combined result of emissions from two large steel com-
plexes (with probably 30 stacks in total) plus smaller plumes from
refineries upwind from the shoreline (sources 14 and 15). The cement
plant, source four (4), can be seen emitting its own discrete plume;
however, it is only detectable for about 10 km out over the lake. It
would seem likely that in the period just prior to ERTS's passage, it was
emitting at a rate far less than its yearly average would suggest.

Measurements of plume spread can be converted into useful information
regarding overwater mesoscale diffusion of pollutants. First, however, it
must be determined what the visible edge of the plume represents in
reality. Sometimes, the visible plume may be correlated to a parameter
such as the point where concentrations drop off to 10% of the centerline
value, or 2.15 σ_y, in the parlance of Pasquill (1961) and Gifford (1961).
If that were the case, then this plume would appear to have a diffusion
rate characteristic of Class E (rather stable atmosphere) in the empirical
classification of atmospheric stabilities used in Gaussian plume diffusion
calculations. Until aircraft measurements of suspended particulates are
made in conjunction with ERTS images to relate plume radiance to some
physical parameter, the actual estimates of plume spread characteristics
must remain tentative.

5. Analysis

An important consideration is the choice of the appropriate ERTS spectral band to provide optimum discrimination of a particulate plume against the underlying surface, in this case water. The plume will be most visible on the photograph when the difference between the optical density of the plume image and the optical density of the lake-surface image is greatest. Plume visibility over a water surface will thus be enhanced by: (1) decrease in the spectral albedo of the lake surface, (2) increase in overall image contrast, and (3) increase in the amount of radiation scattered and/or reflected vertically upwards from the solar beam by the plume. In the case of a plume advecting over a surface of very high spectral albedo, a fourth factor would have to be considered: the extent to which a plume attenuates solar radiation reflected vertically upwards from the surface, a factor dependent on the geometry of scattering and absorption of radiation by the plume.

The first of these major considerations, the spectral albedo of the lake surface, shows a marked variation by wavelength. Direct reflection of solar radiation from the lake surface makes a relatively minor contribution to the variation of lake spectral albedo in the four ERTS bands. Reflection vertically upwards from the lake surface is small, on the order of 2%, and for a solar elevation angle of 40° shows only slight wavelength dependence, with very slightly higher values in the lower wavelengths of the visual spectrum (Kondratyev, 1969).

Far more important in influencing the spectral albedo of the lake is the wavelength dependence of solar radiation absorption within the lake itself. The lower the spectral absorption coefficient within the lake for any wavelength, the greater is the penetration of incident solar radiation into the lake and the greater is the likelihood of back-scattering upward by water molecules and hydrosols, i.e. Rayleigh and Mie scattering respectively. For distilled water, maximum transmissivity occurs at 0.46 μm, and absorption increases rapidly with increasing wavelength, resulting in a darker lake image. As an example, the mean absorption coefficient for pure water in ERTS band MSS-4 is approximately six times less than the coefficient for MSS-5, and the lake thus should appear brighter. Increased amounts of suspended and dissolved matter shift the wavelength of minimum absorption and maximum lake albedo to longer

wavelengths. According to Kondratyev (1969), sea water (and lake water?) typically has minimum absorption near 0.55 μm, which is the center of ERTS band MSS-4.

An additional consequence of the greater transparency of water in the blue and green portion of the spectrum occurs in the case of shallow water, where reflection from the lake bottom may further increase values of surface lake albedo and limit the ability to detect pollution plumes near shore.

Another important factor influencing lake spectral albedo is the variation by wavelength of scattering geometry beneath the lake surface. As Rayleigh scattering has more pronounced backscatter than Mie scattering, increased Rayleigh scattering will produce higher values of lake spectral albedo. In the blue portion of the spectrum, around 40% of all scattering within the lake is Rayleigh scattering by water molecules. In contrast, at the center of band MSS-5 (0.65 μm), only about one in every thirty-five scattering events is typically molecular Rayleigh scattering (Plass and Kattawar, 1969); the rest are strongly forward-scattering Mie scattering events produced by hydrosols. This, coupled with the higher absorption coefficients at longer wavelengths, produces a much darker lake image in band 5 than in band 4. In fact, in the near infrared (MSS-7), water surfaces appear black, the result of very high absorption coefficients of the lake water and the very low amounts of Rayleigh back-scattering at long wavelengths.

All other factors constant, a higher value of lake spectral albedo will produce a higher value of upward hemispheric radiant flux. Surface albedo measures the ratio of radiation reflected or scattered upwards in all directions, i.e. upward hemispheric radiant flux immediately above the surface, to incident downward hemispheric flux. The very narrow scan angle of the ERTS scanner, however, will intercept only that portion of the total flux which is directed vertically upwards. Spectral variations in directional radiation intensity (radiance) in the upward vertical direction may exceed spectral variations in the total hemispheric radiant flux which is produced by difference in lake spectral albedo, including reflection in all directions. In a theoretical study by Plass and Kattawar (1969) of the angular distribution of the radiance over an ocean surface, it was found that for a solar

beam incident angle near 40% (as in the present study) and a wavelength of 0.65 μm (MSS-5), a pronounced minimum of upward radiance in the vertical direction occurs which is an order of magnitude smaller than maximum values found near the horizon. For shorter wavelengths, however, upward radiance is distributed much more uniformly over all zenith angles, and the radiance value in the vertical direction is several times greater than at 0.65 μm. If a similar qualitative relationship holds over a turbid lake, then the greater angular variations of radiance at longer wavelengths would further accentuate differences in spectral albedo to produce darker lake images with increasing wavelength.

The second major consideration limiting our ability to detect particulate plumes against an underlying surface is reduction of overall image contrast. Atmospheric Rayleigh scattering and Mie scattering from haze or pollution layers generally act to increase overall radiance. Because image density of a positive transparency ideally is inversely proportional to the logarithm of exposure and hence, in the case of ERTS imagery, to the logarithm of the radiance, a given increase in radiance due to atmospheric scattering will produce a greater decrease in image density for a low radiance target than for a high radiance target. As a result, the photographic image of a low - albedo target such as a lake shows a greater increase in brightness due to atmospheric scattering than does a highly reflective target such as a cloud or pollution plume, and overall image contrast is reduced. Because scattering varies with wavelength, maximum inherent image contrast (defined for convenience as the difference in photographic density between a target having an albedo equal to unity and a target with zero albedo), will also show variation between spectral bands.

Greatest variation of maximum inherent image contrast between ERTS spectral bands occurs as a result of sky luminance produced by Rayleigh scattering. Although Rayleigh scattering is most pronounced at the short - wavelength end of the visual spectrum, the average Rayleigh scattering coefficient in ERTS band MSS-4 (0.5 to 0.6 μm) is still relatively high, amounting to 45% of the coefficient for 0.4 to 0.5 μm (Kondratyev, 1969), but decreases rapidly for longer wavelengths.

The spectral variation of Mie scattering by atmospheric aerosols
is much less than for Rayleigh scattering and is marked by gradual
decline with increasing wavelength. Computer simulation models of
Rayleigh and Mie scattering in a normally hazy atmosphere (Plass and
Kattawar, 1968) indicate that maximum inherent image contrast (as
defined above) may be over twice as great at 0.7 μm as at 0.4 μm,
and maximum inherent image contrast is even greater in the near
infrared. Increasing aerosol content increases the contribution of
Mie scattering, produces a more uniform distribution of radiance over
all zenith angles (i.e. more isotropic), and increases values of upward
radiance in the vertical direction. The resulting reduction of image
contrast with increase in aerosol content occurs for all wavelengths,
but is most pronounced for shorter wavelengths of the solar spectrum
(Plass and Kattwar, 1970).

The combined effects of high lake spectral albedo and low inherent
image contrast can be seen by examining Fig. 5. Although urban features
of the Chicago-Gary area, regions of high turbidity in Lake Michigan,
and the deck of altocumulus to the northeast are readily visible, plumes
advecting over the lake from Gary and Chicago are virtually undetect-
able at distances exceeding 5 to 10 km downstream from the lakeshore
because of the bright lake and reduced image contrast. Attempts to
enhance contrast photographically through dodging and use of high
contrast paper rendered plumes visible only very near shore where
particulate concentrations were highest.

From the above discussion, the optimum spectral band for plume
tracking over a lake, in the absence of ice cover, might be expected to
fall in the near - infrared range. For band MSS-7 (0.8 to 1.1 μm), sky
luminance is negligible, and a high absorption coeffieient for the lake
water produces very low spectral albedo values and a very dark lake
image on a positive photograph. For liquid-water clouds, whose albedo
is practically independent of wavelength up to 1.3 μm (Kondratyev, 1969),
band MSS-7 does indeed provide maximum contrast in image density between
cloud and lake. Such does not seem to be the case for particulate
plumes, however, because of a third major consideration: the spectral
variations in albedo of a dense particulate plume. Data on the geometry

of multiple scattering and diffuse reflection from pollution plumes are limited. However, tables of primary Mie scattering (deBary et al, 1965) indicate a dependence of angular scattering intensities on wavelength, as mentioned above. For the present case, considering scattering vertically upwards from a solar beam with an elevation angle of 40°, primary scattering coefficients in the near - infrared ($1.0 \mu m$) are only 45 to 75% of the values at the center of the green band ($0.65 \mu m$). Furthermore, computer simulation models of short-wave radiative transfer in a highly turbid aersol layer (Plass and Kattawar, 1972) show higher values of upward radiance (measured at the top of the atmosphere) at $0.7 \mu m$ than at $0.9 \mu m$ (within band MSS-7) for all zenith angles. If the same qualitative relationship holds in the case of multiple scattering in a highly turbid particulate plume, then maximum inherent brightness should occur in the lowest visual wavelengths rather than in the near - infrared.

Thus from various theoretical considerations it would appear that the poorest plume discrimination above a water surface would be in the shortest wavelengths, as confirmed by MSS-4 (Fig. 5). On the other hand, while it was initially expected that the near - infrared (band 7) would optimize plume contrast over water, as is the case with liquid-water clouds, the higher inherent brightness of plumes in the visible spectrum results in the "red" band being the best for smoke detection. The plumes were visible in bands MSS-6 and 7; band 5, however, provided the best compromise between the high lake spectral albedo and low contrast of the shorter wavelengths and the diminished plume albedo in the longer wavelengths.

6. Conclusions and Future Research

From this case study, it now appears highly likely that when the proper meteorological conditions (south-southeasterly winds) coincide with an ERTS passage, we will be able to detect major air pollution plumes entering the Southeast Wisconsin "airshed" from sources over 100 km removed. If it can be shown that this inter-regional pollution transport contributes significantly to the observed particulate levels in the Milwaukee area, a most interesting question will arise. If Southeast Wisconsin fails to reach its air quality standards for suspended particulates, should it be penalized for the "sins of emission" of other regions?

While ERTS images such as the ones discussed are of great interest in themselves, their value is somewhat limited by the unavailibility of actual "ground truth" supporting data. UWM's Air Pollution Analysis Laboratory has now instrumented a Cessna 336 aircraft with an array of air pollution and meteorological sensors. Included are fast response devices for monitoring total suspended particulate mass loadings and particle concentrations in several size ranges. Onboard processing and tape data logging will make it possible to fly repeated profiles of selected plumes coincident with ERTS. Thus it may be possible to determine radiance/mass loading relationships, and also to ascertain how well the actual plume conforms to the Gaussian profile so often imposed in numerical studies. Densitometric analysis of ERTS negatives would also accompany such studies.

Unless they are unusually dense, smoke plumes are harder to detect over land than over water. Land surfaces are generally much brighter than water and exhibit marked spatial and seasonal variations in radiance. Using false-color infrared, at least during summer, seems to be reasonably successful at times, but visual detection of many plumes may not be routinely possible. The next step of analysis then should be smoke detection by computerized pattern recognition techniques employing the primary ERTS digital tape data rather than photographically reconstructed products.

7. Acknowledgements

Table 1

Estimated annual tonnage of suspended particulate emissions from major point sources in the Chicago Interstate Air Quality Control

NO.	TYPE SOURCE	EMISSIONS (TONS/YEAR)
1	Steel Mill/Fabrication	20,394
2	Steel Mill	82,474
3	Cement Plant	142,675
4	Fossil Fuel Power Plant	1,952
5	Steel Complex	
6	Steel Complex (open burning)*	88,597
7	Steel Complex	
8	Steel Complex	
9	Steel Mill	24,000
10	Fossil Fuel Power Plant	4,752
11	Steel Mill/Fabrication	4,000
12	Steel Mill	5,900
13	Oil Refinery	1,596
14	Oil Refinery	1,978
15	Oil Refinery	1,014
16	Steel Mill	3,562

*Probably short-lived ground site

Figure Captions

Figure I - Photograph, looking east, from University of Milwaukee-Wisconsin campus, showing layers of iron oxide red smoke over Lake Michigan, during brisk south-southeast winds and very stable conditions in March, 1973. The source of the smoke is presumably the Chicago-Gary area.

Figure 2- Smoke plume from large fossil fuel power plant located south of Milwaukee's Mitchell Airport (MKE). This plume, photographed looking north from an NCAR Queen Air on 22 August 1968 was advecting over a relatively cold lake. The air was so stable that the plume could be seen extending for over 100 km to the east.

Figure 3 - Photograph (looking north) of a portion of the Chicago-Gary industrial complex, taken from an NCAR Queen Air, on the morning of 15 July 1968. The numbers refer to the sources listed in Table I.

Figure 4 - Synoptic conditions, I000CST, I October 1972. An overcast area of altocumulus is present to the north and east of the study area. Isobars every 2mb, one wind bar equals 5 kts. Inset shows 0600CST Peoria, Illinois radiosonde.

Figure 5 - ERTS-I image, MSS-4 (0.5 - 0.6 micrometers) taken I003CST, I October 1972. Aviation weather observations superimposed.

Figure 6 - ERTS-I image, MSS-5 (0.6 - 0.7 micrometers). Smoke plumes clearly visible. Numbers refer to sources listed in Table I. Altocumulus clouds are visible to northeast. Patches of cirrus and near shore water sediments can also be noted.

8. References

deBary, E., B. Braun, and K. Bullrich, 1965: Tables related to light scattering in a turbid atmosphere, Volume I. Air Force Cambridge Research Laboratories Special Report No. 33, Bedford, Massachusetts.

Gifford, F. A., 1961: Uses of routine meteorological observations for estimating atmospheric dispersion. Nuclear Safety, 2, 47-51.

Kondratyev, K. Ya., 1969: Radiation in the Atmosphere. Academic Press, New York.

Langer, G., C. Biter, and A. Dascher, 1968: An automated aircraft instrumentation system for cloud nucleation studies. Bull. Amer. Meteor. Soc., 49, 914-917.

Lyons, W. A., 1966: Some effects of Lake Michigan upon squall lines and summertime convection. Proc. 9th Conf. Great Lakes Res., Intl. Assoc. for Great Lakes Res., Ann Arbor, Michigan, 259-273.

-----, 1970: Numerical simulation of Great Lakes summertime conduction inversions. Proc. 13th Conf. Great Lakes Res., Intl. Assoc. for Great Lakes Res., Ann Arbor, Mich., 369-387.

-----, and S. R. Pease, 1972: "Steam Devils" over Lake Michigan during a January arctic outbreak, Mon. Wea. Rev., 100, 235-237.

-----, and H. S. Cole, 1973: Fumigation and plume trapping on the shores of the Great Lakes during stable onshore flow. J. Applied Meteor., 12, 494 - 510 .

-----, and E. Rubin, 1973: Instrumenting a Cessna 336 for air pollution measurements. Air Pollution Analysis Lab., Report No. 6, University of Wisconsin-Milwaukee, in press.

MacCallum, D. H., 1973: Availability of ERTS-1 data. Bull. Amer. Meteor. Soc., 54, 112-114.

Pasquill, F., 1961: The estimation of the dispersion of windborne material. Meteor. Mag., 90, 33-46.

Plass, G. N., and G. W. Kattawar, 1968: Calculations of reflected and transmitted radiance for earth's atmosphere. Applied Optics, 7, 1129-1135.

-----, and -----, 1969: Radiative transfer in an atmosphere - ocean system. Appl. Optics, 8, 455-466.

-----, and -----, 1970: Polarization of the radiation reflected and transmitted by the earth's atmosphere. Appl. Optics, 9, 1122-1130.

-----, and -----, 1972: Effect of aerosal variation on radiance in the earth's atmosphere - ocean system. Applied Optics, 11, 1598-1604.